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Absolute Measurements of Gravity

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13. ABSTRACT *(Maximum 200 words)*
The Institute of Geophysics & Planetary Physics (IGPP) has completed a two-phase, three-year program of absolute gravity research and development. The development phase included modifications to an existing absolute gravity meter. Our goal was to incorporate state-of-the-art technology and portability while maintaining meter accuracy. The research phase included both field testing of the modified meter and the establishment of new absolute gravity sites. In particular, we were able to survey absolutely a series of closely spaced sites along existing calibration lines.

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1. Overview of the IGPP Absolute Gravity Program

Modern geodetic techniques make it possible for us to observe deformation due to plate tectonics in near real time. What was once inferred from geologic observations is now routinely evident in records produced by precise distance measurements over long baselines [*Christodoulidis et al.*, 1985]. Unfortunately, the longest space-based records of displacement, observed with Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR), do not yet have adequate resolution to discern *vertical* motions clearly. The growing use of the Global Positioning System (GPS) will not provide much improvement since its resolution in the vertical coordinate is not as good as in the horizontal, and over baselines of order 100 km or longer, its resolution is no better than VLBI or SLR. Leveling is too costly to provide wide coverage over long baselines.

We are learning much about the earth through observations of horizontal motion. Detection of vertical displacements, presently evident in all but extreme cases only through the existence of mountains and terraces, would be a useful complement to the much more thoroughly studied lateral case.

The problem of detecting vertical deformation is growing in importance through the recognition of global warming and its relationship to mean sea level. Coastal tide-gauge records from around the world show a confusing picture because real sea level rise cannot be separated from subsidence of the land around the tide gauge [*Carter et al.*, 1989].

Measurements of the earth's gravity provide an economical supplement to the problem of vertical control. Because the value of g (the local acceleration due to gravity) decreases as the distance to the earth's center increases, records of g give an indirect way of looking for secular variations in the vertical coordinate. When made in conjunction with independent means for determining vertical displacement, the relationship between a change in height and a change in gravity can provide important insight into the mechanism responsible for the deformation.

The IGPP absolute gravity program has been ongoing for over seven years. The program's goal has been to repeat absolute measurements of gravity at a number of stations in California to detect vertical deformation in the earth's crust. The instrument constructed here utilizes a test mass that falls freely in a vacuum while being tracked with a laser interferometer, avoiding the sources of error that would make it otherwise impossible to interpret secular changes in gravity as being due to crustal deformation rather than instrument drift. The instrumental accuracy corresponds to a sensitivity in height of about 3 cm.

Five-year-long records of gravity constrain the maximum rate of vertical deformation that can be occurring at a number of locations in California. At one of our sites we see a gravity variation well correlated with an independent measure of the vertical (VLBI) that may or may not be coincidental.

A primary objective of this work is to further the development and deployment of a free-fall absolute gravity meter. This project is partly supported by the National Science Foundation, covering costs of repeated instrument deployment and maintenance for generally monitoring gravity

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changes in California. The support from the Air Force Geophysics Laboratory is for 1) monitoring gravity changes specifically in the Mammoth Lakes region--an area of active volcanism--and for 2) evaluating and improving the accuracy of the absolute gravity instrument, while furthering the instrument's reliability and ease of deployment.

1.1. The Instrument

The majority of gravity measurements are made with relative gravimeters, such as the LaCoste-Romberg instruments. Such devices measure only gravity differences, and data interpretation assumes that the gravitational acceleration g at a base point or set of base points is unchanging over the period of interest. This inherent assumption is difficult to justify over long periods during which tectonic activity might produce gravity changes across broad areas. An absolute gravity meter (AGM) has no ambiguous reference level since it directly measures the acceleration of g with respect to atomic standards of length and time.

A free-fall absolute gravity meter is essentially a Michelson interferometer in which one arm of the interferometer is a freely-falling corner cube retroreflector placed in a vacuum chamber. The other arm ends in a corner cube mounted in a seismometer mass, in order to isolate it from ground vibrations. The interferometer senses the motion of the falling object; digital electronics provide timing information. The position-time data are used to solve the equation of motion of a freely-falling body and thus to determine g.

The IGPP AGM has a nominal accuracy of 10 μGal or approximately $10^{-8} g$. Because the free-air gravity gradient is about 3 μGal/cm, this translates to a sensitivity to height change of about 3 cm. Great care is taken to suppress non-gravitational forces acting on the falling body, such as residual air drag and electrostatic forces. The measurements of length and time are accurate to a few parts in 10^9, and are referenced to atomic standards of length and time. *Arnautov et al.* [1987] presented the results of an absolute gravity meter intercomparison in 1985, which is a test of instrument accuracy.

Construction of the IGPP absolute gravity meter was started in 1982, and the first measurements were made with it in 1983. The instrument's design was based on the Joint Institute for Laboratory Astrophysics (JILA) prototype [*Faller et al.*, 1979; *Zumberge et al.*, 1982].

Figure 1 is a simplified diagram of the IGPP absolute gravity meter [*Zumberge et al.*, 1986; *Sasagawa*, 1989]. A Zeeman-stabilized laser [*Zumberge*, 1985; *Sasagawa and Zumberge*, 1989] illuminates the Michelson interferometer. The falling corner cube is enclosed in and tracked by a miniature elevator to protect it from the influences of drag from residual air molecules and forces from electrostatic fields.

Each half wavelength that the corner cube falls gives a shift of one fringe at the detector end of the interferometer. These fringes are counted and the times of occurrence of a subset of them are recorded by a microcomputer. The times are measured using a commercial time digitizer referenced to a rubidium frequency standard. The acceleration of the falling corner cube can be calculated from the resulting time versus position data. With our instrument, it takes about 18 minutes to make 100 single drop measurements, resulting in a statistical uncertainty of usually less than 10 μGal.

A number of experiments have been performed to determine the accuracy of the instrument. These include the replacement of the falling mass with one made of molybdenum rather than aluminum. This increased the mass of the falling object without changing its shape, and it would have resulted in a different g value if any of a wide variety of non-gravitational forces were present. None were found.

One potential source of systematic error in absolute gravity measurements is the vibration of the floor during the measurement. Background vibrations from seismic sources and human activity

increase the drop-to-drop scatter in the gravity determinations, but are not a source of systematic error because the accelerations associated with these sources average to zero over many cycles. However, floor vibrations initiated by the act of dropping the mass at the beginning of individual gravity determinations have a fixed phase relationship to the measurement and are therefore a potential source of systematic error. One of our objectives has been to evaluate the severity of this effect in absolute gravity meters in general and in our instrument in particular.

A series of tests were carried out in which the floor vibrations caused by the drop were made to vary in amplitude. These vibrations have a characteristic frequency of approximately 80 Hz and an amplitude of a few nanometers, and are detected in the residuals to the least-squares fit of the time versus position data. We found that we could vary the vibration amplitude by decoupling the dropping chamber from the laboratory floor with differing combinations of lead disks and rubber pads. Similar vibration isolators placed under the optics base were also effective in reducing vibration, yet they allowed the optics to tilt, causing a cosine error in the length measurement. One experiment included mounting the optics base on a vibration isolated optical table separate from the dropping chamber. A dramatic decrease in the residuals was noted.

We performed an important test of the effect of vibration at our absolute site in Pasadena, California. The site is in the California Institute of Technology's Kresge Seismological Lab. This is one of the sites where a seismic pier is available for the measurements. We built aluminum stands in our shop to allow the dropping chamber to be suspended over the seismic pier without being in direct contact with it or the gravity meter optical system placed on the pier. Data taken with this configuration showed almost no systematic floor vibration.

The equipment was then reassembled on the concrete floor adjacent to the seismic pier in the normal configuration for sites with no seismic isolation pier. When corrected for site relocation (as determined with a LaCoste & Romberg relative gravity meter), the gravity values determined under the two configurations agreed to within 4 μGal. This agreement, in light of the large vibrations encountered with only the second configuration, lends credence to our conclusion that such vibrations are not a source of systematic error in our system.

1.2. Instrument Modifications

A source of not infrequent breakdown of the absolute gravity meter is the portable ion-pump supply. The ionization vacuum pump requires 5.5 kV of DC power at 1 - 5 mA to retain the high vacuum level during transport. This removes the need for time-consuming pump-down after arrival at the gravity station.

Originally we used an in-house assembled power supply that is built around a module manufactured by Crestronics (Santa Anna, Calif.) to convert 12 V DC from the vehicle's battery to 5.5 kV DC. The module is essentially a high gain DC-DC converter. The failure mode of the 12 V to 5.5 kV module is that it achieves the high gain in a single stage. This puts a severe demand on the insulation separating the high voltage part of the circuit from the low voltage side. We have built a two-stage converter which first converts the 12 V DC to 110 V AC, then converts that to 5.5 kV DC. This unit has been in use in the field now for several years without breakdown.

Another important instrument modification has been to incorporate a commercial avalanche photodiode in place of a photomultiplier tube that was used originally. The solid-state detector's wide bandwidth eliminates the systematic error that can be caused by frequency dependent phase shifts in the timing electronics.

In our testing of the Zeeman stabilized laser used to illuminate the interferometer we detected a temperature coefficient [*Zumberge*, 1985]. Correction for the laser's temperature dependence is made by referencing the ambient air temperature and a temperature sensor bonded to the laser tube.

1.3. Field Sites

Figure 2 presents a map of gravity sites in California, Alaska, and Nevada surveyed by the IGPP instrument. At an accuracy level of 10 μGal, it is possible to begin detecting gravity changes over the course of five years or less.

As of October 1989, the IGPP absolute gravity meter has occupied 22 sites in three countries, accumulating over 120,000 drops in 115 measurement sessions (site descriptions may be found in *Zumberge et al.* [1983], *Zumberge et al.* [1986], and *Sasagawa et al.* [1989]). Gravity values are all transferred to the floor, and the transfer uncertainty is included in the final uncertainty estimates. The data have been edited for known instrumental errors, which corrupt only 8 site occupations.

Figure 3 is a series of plots displaying the gravity records at most of our California sites where we have made multiple observations. The sampling interval and sample size at each site is quite variable. Sample sizes range from two measurements at each of two sites to 26 measurements at PFO. The measurement uncertainties are nominally 10 μGal, ranging from 8 μGal to 23 μGal. *Zumberge et al.* [1982] discuss the error sources in detail. The IGPP AGM data set spans five years, from mid-1984 to mid-1989. The points plotted prior to 1984 (open circles) are observations made with the JILA prototype [*Zumberge et al.*, 1983].

2. Selected Gravity Records and Interpretations

Table 1 presents the computed linear gravity changes for 10 sites using the IGPP data set. (We have omitted the data from one of our California sites, OVR, because one of the two observations there has serious errors.) The F test [*Bevington*, 1969] presented in the last column assesses the variance reduction afforded by adding to the model a term linearly dependent on time.

Table 1. Secular Gravity Trends

Site	Measurement Interval	N	Station Rate, μGal/yr	χ^2_{N-1}	χ^2_{N-2}	σ, μGal	F-Test[a], % Prob.
EFS	1985.89 - 1989.07	13	5.8 ± 2.6	2.11	1.84	13	12
GLD	1984.53 - 1986.36	3	-18.4 ± 8.9 [b]	2.51	0.42	18	19
MAM	1984.52 - 1989.70	11	-8.4 ± 1.9	4.55	2.85	20	3
MES	1985.55 - 1988.71	5	3.3 ± 3.9	0.97	1.04	9	45
MPK	1985.68 - 1989.66	9	-3.1 ± 2.3	2.19	2.24	13	40
NRC	1984.97 - 1987.77	9	3.0 ± 4.2	0.12	0.06	4	2
PAS	1984.62 - 1989.11	8	3.5 ± 2.5	2.70	2.78	14	41
PFO	1984.32 - 1989.63	26	-1.0 ± 1.3	1.27	1.30	10	48
QHP	1985.65 - 1989.71	5	-3.4 ± 2.5	2.35	2.51	13	45
RSA	1985.04 - 1986.21	2	5.1 ± 12.8	-	-	4	-

a The F test (Fisher test) for the validity of adding the additional rate term can be used as a quantitative choice between two models. The F statistic computes the fractional reduction in χ^2 of the secular model over the constant model. The probability of the null hypothesis that the secular model does not significantly fit the data better than the constant model is computed from the F statistic. Thus only in cases where the value listed in the right-most column is small is there strong justification for a secular term.

b When the observation made with the 1982 JILA instrument is included in the analysis, the rate at GLD is 0.8 ± 3.1 μGal/yr.

For most of the sites, the data do not justify a secular term. The station rates are not significantly different from zero, when compared to the station rate uncertainties. While the

secular model does reduce χ^2 at most sites, the significance of adding the additional parameter $\dot{g}$ is less than 90%. (Note that the apparent increases in χ^2 in Table 1 are artifacts of the use of reduced χ^2 and the small number of data points at certain sites.) In cases where the data are sparse, small N statistics should not be over-interpreted.

The station rate for NRC is effectively zero, but the F test indicates that a secular model is required to describe the data. The fit is controlled by the last point in the time series, which explains the large F test significance; the constant model adequately accounts for the data.

Station GLD has a secular rate change of -18.4 ± 8.9 μGal/yr, measured over 2 years with three observations. When we include the 1982 observation made with the prototype instrument constructed at the Joint Institute for Laboratory Astrophysics (JILA) [*Zumberge et al.*, 1983] the rate is essentially zero; 0.8 ± 3.1 μGal/yr.

Station MAM does have an apparent gravity decrease, of order 10 μGal/yr. This is discussed below. Note that MAM is in a site of resurgent volcanism, and a gravity signal might be expected from geological considerations.

Figure 4 is a stacked time series of the data from the 10 sites listed in Table 1 (EFS, GLD, MAM, MES, MPK, NRC, PAS, PFO, QHP and RSA). The gravity data have been transformed by subtracting the mean g value of each site from the data for that site, forming a group of zero-mean time series. The zero-mean series are then plotted on the same graph.

The secular rate of the stacked zero mean series is 0.2 ± 0.9 μGal/yr. The fit of a secular model is poor and can be rejected at the 83% confidence level. This signal averaging technique indicates that the AGM has no significant linear drift. The standard deviation of the data set is 10.6 μGal, of the same order as the nominal uncertainty of a single measurement. The instrumental error estimate is consistent with the observed repeatability, and implies the error estimate is reliable. Of course, repeatability does not guarantee the absence of systematic errors.

2.1. Piñon Flat Observatory

The Piñon Flat Geophysical Observatory (PFO) is our best absolute gravity site for a number of reasons. The optics base is placed on a 3-m-long isolated gabbro pier, buried for 2 m of its length. The dropping chamber is placed on three separate aluminum stands. This setup decouples the mechanical vibrations of the dropping chamber from the optics base, and provides the least measurement scatter of all the gravity sites. The site is also very quiet in terms of seismic noise and is easy to reoccupy, leading to a frequent measurement schedule. The observatory also has a number of other geophysical sensors, including long-baseline strainmeters and tiltmeters, with which to compare the data from the absolute gravity meter [*Wyatt and Agnew*, 1989].

Instruments at PFO continuously monitor the local barometric pressure and water table levels. These data are used to compute the gravity effects of barometric pressure variations and changes in the water table. The effects of polar motion were computed from polar orientation data. Ocean loading tidal components were modeled also for PFO. The RMS gravity variation induced by these environmental corrections is less than 3 μGal.

Figure 5*a* reproduces the PFO data on a larger scale, showing only the IGPP results. A filtered version of the data (the solid curve in Figure 5*a*) reveals a "trend" with amplitude of the same order as the estimated total uncertainty, 10 μGal. The signal may be a real change in g, an instrumental error, or simply coincidental. If the source of the variation is instrumental in origin and site independent, the trend should appear in the data for the other sites. A correlation or scatter plot was used to investigate this hypothesis.

The interpolating curve shown in Figure 5*a* was generated by a low-pass filtering algorithm [*Press et al.*, 1986]. A cubic spline fit was used to generate the continuous curve. Averaging over 6 data points was subjectively chosen as a reasonably smooth approximation of the data. A scatter

plot (Figure 5*b*) was then generated using the smooth PFO data estimates as the horizontal coordinates and zero-mean data from the 10 previously described sites as the vertical coordinates of the scatter plot points.

There is no significant correlation between the PFO absolute gravity observations and those obtained at our other sites (the correlation coefficient is 0.06 and the correlation probability is negligible). The plot is limited in the horizontal axis due to the relatively small range of g observed at PFO. If a small but detectable instrumental trend were present, one would expect the very quiet and densely sampled PFO data set to resolve the trend. Thus it is unlikely that the AGM has a site independent error which varies in time.

One way to estimate the level of gravity variation that might be expected at PFO is to model the region as a block undergoing strain whose rate can be limited by the PFO strainmeter records. A simple model after *Savage* [1984] predicts the gravity changes induced by uniaxial compression acting on a rectangular lithospheric block. Based on this model, one can calculate an effective gravity-elevation coefficient of +0.27 μGal/cm. This predicts a gravity increase of only 0.07 μGal/yr for an uplift rate of 2.5 mm/yr (based on the observed strain-rate limit of 10^{-7}/yr). The observed gravity rate of -1.0 ± 1.3 μGal/yr is consistent with this "back of the envelope" estimate. This predicted strain-derived gravity signal is below the resolution of the observed signal. What is significant is that the absolute gravity data are consistent with no change above the limits of detectability, as predicted by this simple model.

Secular tilt measurements at PFO indicate tilt down towards the west of 1.1×10^{-7} rad/yr in the period 1984 to 1986 [*Wyatt and Agnew*, 1989]. PFO is 12 km from the San Jacinto fault and 25 km from the San Andreas fault. The estimated absolute value of the elevation change is 3 mm/yr for a deformation length of 25 km (chosen somewhat arbitrarily); the sign of the elevation change cannot be determined from the tilt data alone. This is a rough calculation, since the true extent of the deformation is not known. By multiplying the tilt-estimated elevation signal by the free air gradient, the expected magnitude of $\dot{g}$ is 0.9 μGal/yr. The tilt-derived gravity signal is below the detection level of the absolute gravity meter. Again, the gravity meter signal is consistent with the signal derived from tilt observations.

Another set of geodetic measurements are vertical position estimates provided by mobile VLBI data at PFO. Figure 6 is a comparison of elevation and gravity measurements at PFO made with the IGPP AGM and mobile VLBI baseline vertical component estimates, for the baseline PFO to MOJAVE12 [*Ma et al.*, 1989]. The baseline is only 195 km long, and thus the baseline vertical components are similar to the local vertical directions at either site. The gravity time series is converted to elevation changes by applying the reciprocal free air gravity gradient (γ^{-1} = -0.325 cm/μGal). It is simplistic to use the free-air gradient, yet a more complicated model is not yet warranted by the data. The gravity series plotted has been corrected for ocean loading, barometric pressure, polar wander, and water table variations.

The VLBI subsidence rate estimate is - 17.4 ± 11.1 mm/yr, with a high probability that the elevation is constant. The $\dot{g}$ estimate for the data plotted is 0.9 ± 1.5 μGal/yr or an equivalent elevation change of -3 ± 5 mm/yr, with a 22% probability that g is constant. Both sets can be consistently interpreted as showing no significant deformation, within the limits of experimental uncertainty.

The VLBI data series is somewha' noisier than the gravity series, with a weighted RMS scatter about a linear fit of 4.54 cm. The gravity series has a standard deviation of 11 μGal in gravity or 3.6 cm in inferred elevation estimates. Individual VLBI elevation estimate uncertainties range from 4 to 8 cm. Each individual gravity estimate has an associated total uncertainty estimate of ≈ 10 μGal or an equivalent elevation uncertainty of 3.3 cm.

To this point in the discussion we have considered only the secular rates in various time series, essentially because there is little justification in the data to assume a more complex model. There is, however, an intriguing correlation between the VLBI data and gravity, beginning in 1986. This correlation, perhaps coincidental, is under investigation. If this correlation were indeed real, a more complex description than the linear model would be needed to describe the gravity and vertical data to retain consistency with the strain and tilt records. When the fitted trend plotted in Figure 5a is interpolated to obtain calculated values of g at times corresponding to the VLBI observations, a correlation probability of 95% is obtained. Because of this, we must entertain the possibility that there truly is vertical motion at PFO and we should find a model that can reconcile the gravity and VLBI data with the limits set by the continuous strain and tilt records. This is currently underway.

2.2. Long Valley

Long Valley is a site of contemporary deformation due to volcanic processes [*Hill et al.*, 1985; *Rundle and Hill*, 1988]. A resurgent volcanic dome beneath the center of the caldera grew dramatically between 1975 and 1984 causing an uplift of 400 mm. Based on simple volcanic models that approximate the expected g signal for Long Valley, one would expect a 70-90 μGal gravity decrease associated with that uplift. If the uplift continued at such a rate, this g signal would be easily observed. Long Valley was chosen for intensive study with the absolute gravity meter. The actual relationship between gravity change and height change can reveal important information on the associated deformation mechanism.

The gravity network in Long Valley, California, consists of two absolute stations and 11 relative sites. Measurements began in 1984 with one absolute survey, and continue to be made to the present day.

The primary site, station MAM, is located in the Mammoth Lakes Forest Service Visitor's center, ≈ 4.5 km west of the point of maximum uplift observed on highway US 395. The second absolute site is in the former Mammoth Lakes School District Elementary School, ≈ 4.5 km east of the US 395 uplift maximum. Because the site is unheated it cannot be occupied in the winter; in those periods relative ties are made between MAM and MES.

As of September 1989, eleven absolute measurements were made at site MAM and five at site MES. Figures 7 and 8 present the time series of these surveys. The data have been corrected for ocean loading and polar motion.

The MAM data indicate a gravity decrease. A linear least squares fit to the corrected absolute data determined a station rate at MAM of -8.2 ± 1.9 μGal/yr (corresponding to an uplift of order 2.7 cm/yr). The fit is fairly poor, with $\chi^2_{N-2} = 2.77$. However, the F test rejects use of only the constant model at the 2% level. Polar motion and ocean loading corrections have an insignificant effect on the station rate determinations; Table 1 presented the rate determinations for the uncorrected data.

The computed station rate for MES is 5.3 ± 3.9 μGal/yr, with $\chi^2_{N-2} = 0.57$: a reasonable fit. The linear gravity model for MES is not supported at the 90% confidence level. Again, polar motion and ocean loading corrections do not significantly affect the station rate determinations. As previously mentioned, the MES site cannot be occupied during the winter months. The MES data set was extended by measuring the gravity difference between MES and an absolute g determination at MAM. These additional data points are known as transferred absolute g values, or g_T data (and are plotted with open diamonds in Figure 7). The addition of three g_T data points to the MES time series does not change the station rates in a statistically significant manner.

Although gravity decreases associated with uplift have been observed in the past in Long Valley, we do not believe that the signal evident in Figure 7 is the result of crustal deformation. Leveling measurements in the region have indicated that the rate of uplift over the caldera slowed significantly before we began our measurements there. Contemporary leveling data and triangulation [*Langbein et al.*, 1987] show vertical deformation proceeding at less than 1 cm per year. Records of ground water content at a number of monitoring wells in the region show a general drop in the water table during the period covered by our gravity record. Individual well level records do not correlate well with one another, indicating that each samples localized hydrology [*Farrar et al.*, 1985 and 1987]. The well nearest to MAM (4 km away) shows a drop of 7 m between mid-1984 and 1988. A porosity of 12% (quite reasonable for the area) would be needed to explain the MAM gravity.

3. Summary

The gravity records we have obtained in California averaged over the period sampled show that if uplift or subsidence is occurring, the secular rate must be no more than 1-2 cm/yr at most of our sites. This bound is about as small as can be set using other geodetic techniques, and the cost of absolute gravity measurements compares favorably with these.

We do observe some gravity changes that are barely significant statistically. We have attempted to reconcile these changes with other geodetic techniques and assess the likelihood that they are due to environmental effects or real uplift.

Another explanation for the small gravity variations seen is that they are all solely artifacts of the instrument, being due to an unrecognized systematic error that changes in time. We are constantly checking for errors of this type and we always conclude that the uncertainty estimates we quote are good. Aside from one instance, we get very good agreement when comparing gravity differences determined with relative meters between two nearby absolute sites surveyed closely in time. (The one exception to this is a discrepancy between absolute differences and a relative tie between our two Long Valley sites).

The IGPP absolute gravity meter shows promise as a tool for studying vertical deformation. We now have high confidence in the estimated accuracy of 10 μGal. More data are needed to better quantify deformation induced gravity changes, but the records obtained thus far serve as a good set of baseline measurements.

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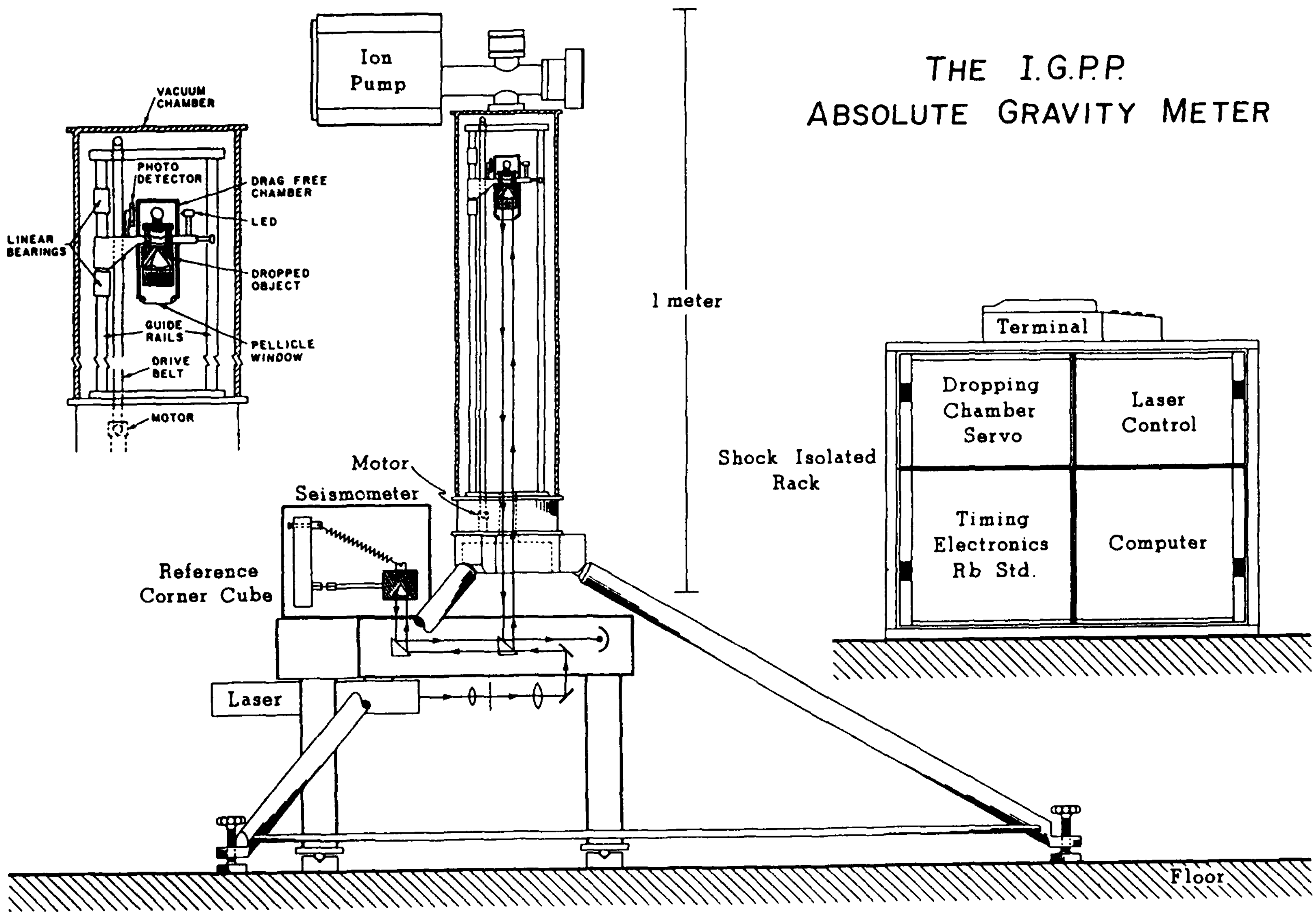

THE I.G.P.P.
ABSOLUTE GRAVITY METER
VACUUM CHAMBER
PHOTO DETECTOR
DRAG FREE CHAMBER
LED
LINEAR BEARINGS
DROPPED OBJECT
GUIDE RAILS
PELLICLE WINDOW
DRIVE BELT
MOTOR
Ion Pump
1 meter
Motor
Seismometer
Reference Corner Cube
Laser
Shock Isolated Rack
Terminal
Dropping Chamber Servo
Laser Control
Timing Electronics Rb Std.
Computer
Floor

Figure 1.

IGPP Absolute Gravity Sites

Figure 2.

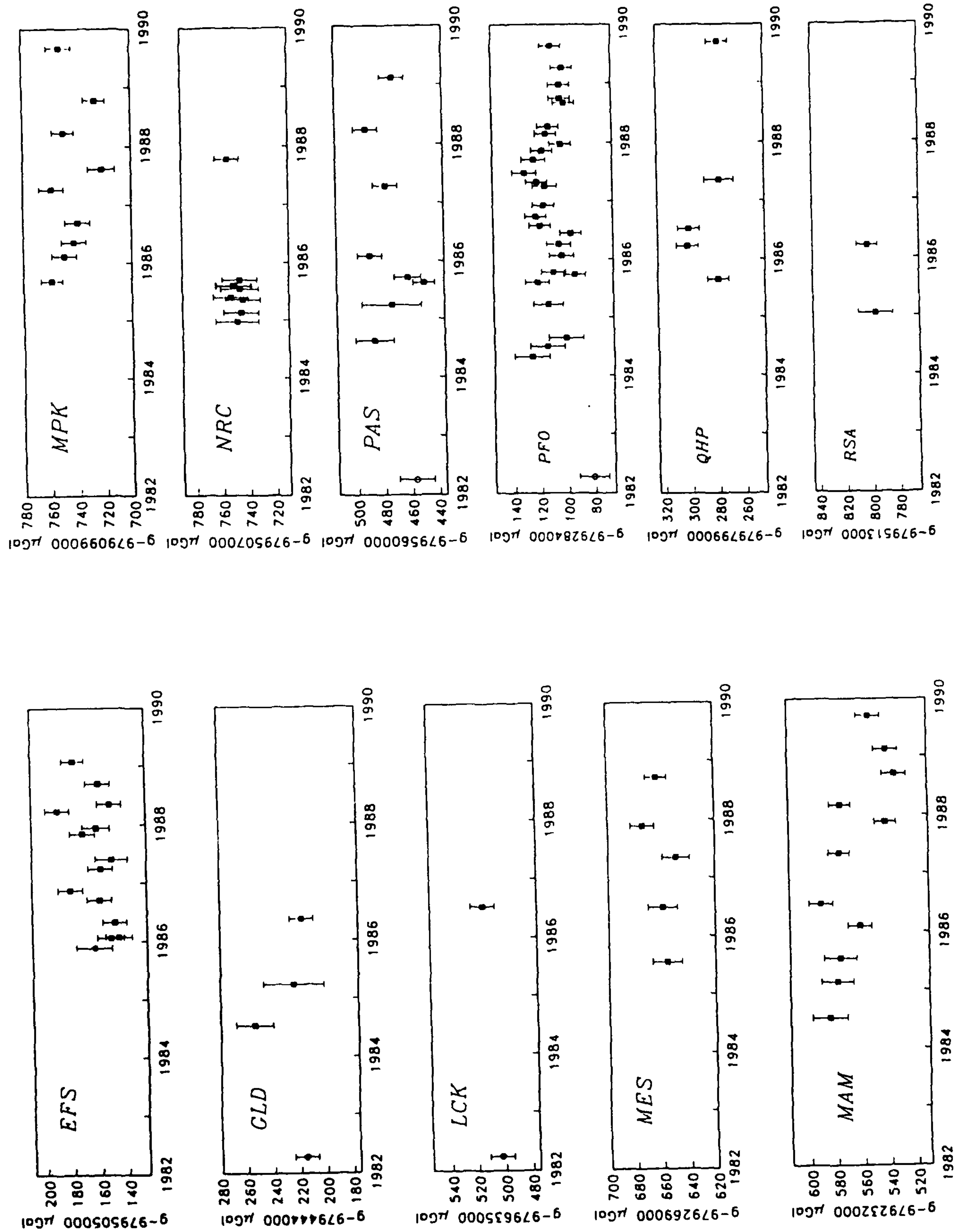

MPK
g-979099000 μGal
NRC
g-979507000 μGal
PAS
g-979560000 μGal
PFO
g-979284000 μGal
QHP
g-979799000 μGal
RSA
g-979513000 μGal
EFS
g-979505000 μGal
GLD
g-979444000 μGal
LCK
g-979635000 μGal
MES
g-979269000 μGal
MAM
g-979232000 μGal
1982
1984
1986
1988
1990

Figure 3.

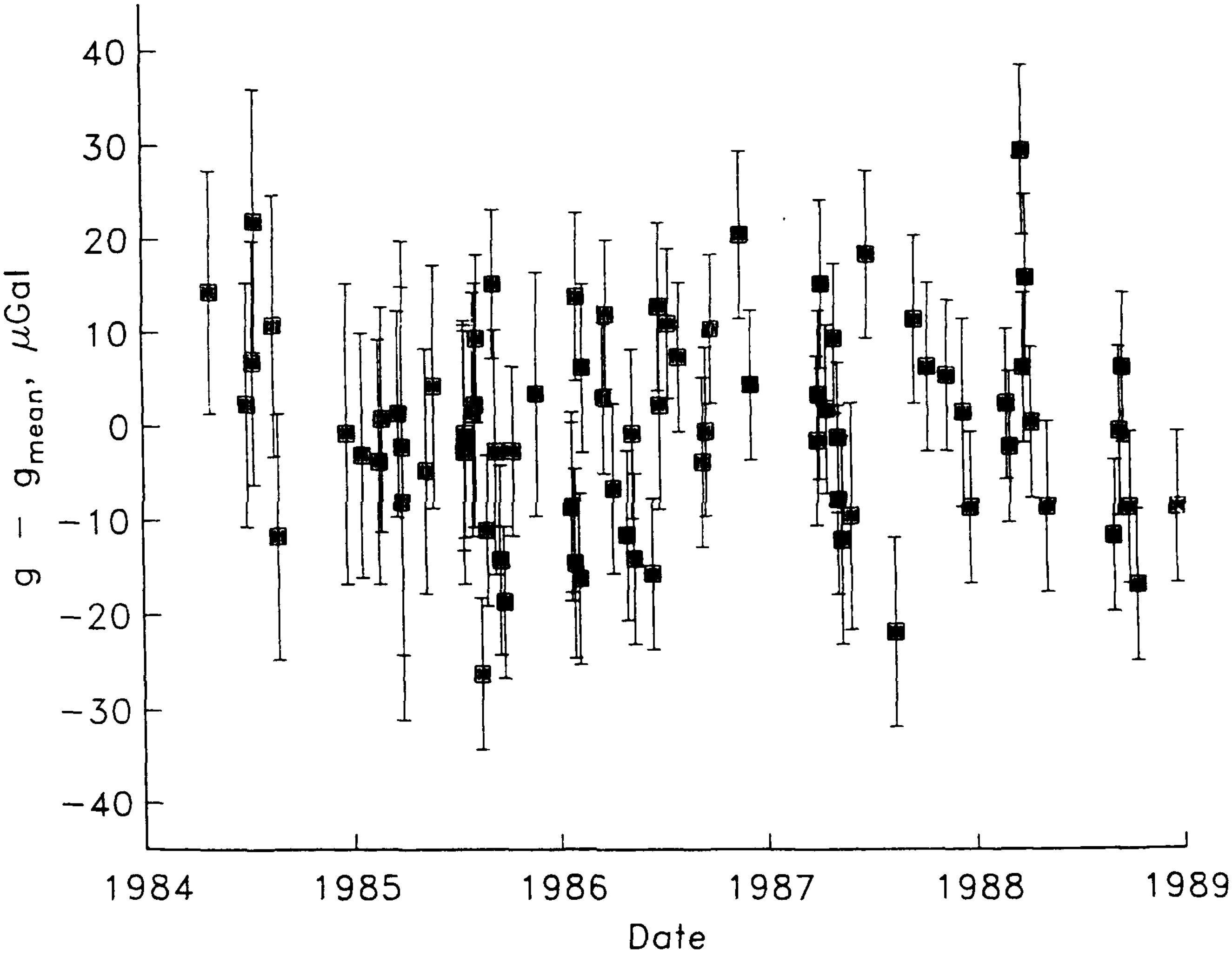
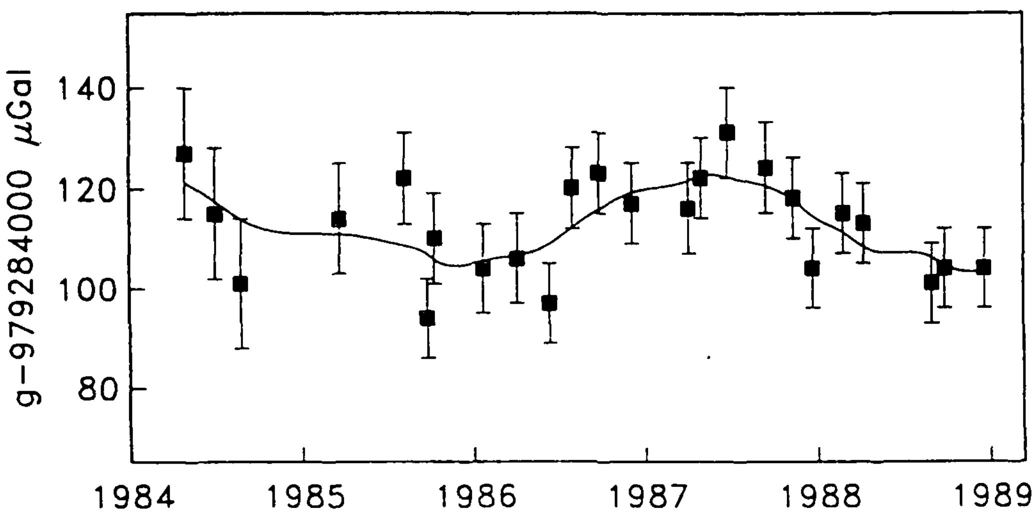
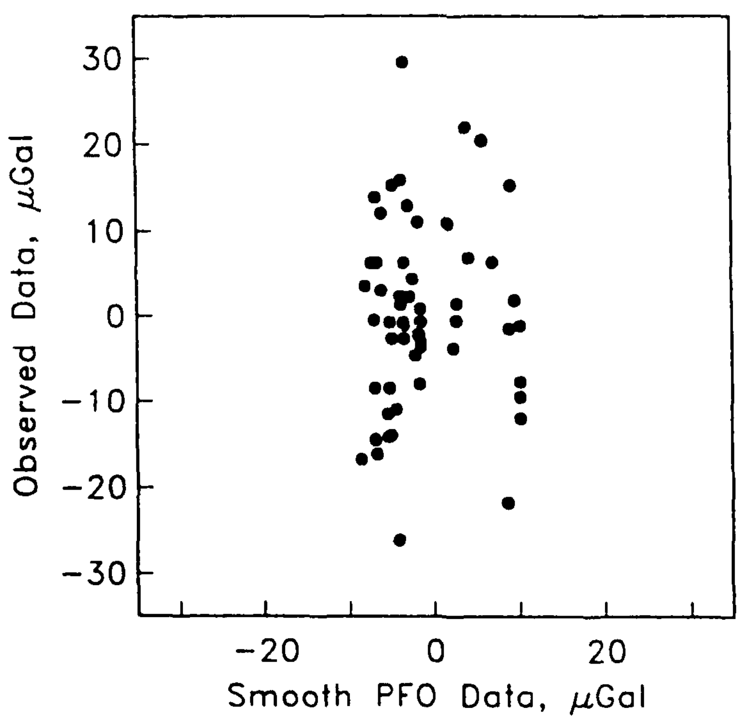

40
30
20
10
0
−10
−20
−30
−40
g − g_mean, μGal
1984
1985
1986
1987
1988
1989
Date

Figure 4.


g-979284000 μGal
140
120
100
80
1984
1985
1986
1987
1988
1989

(a)


Observed Data, μGal
30
20
10
0
−10
−20
−30
−20
0
20
Smooth PFO Data, μGal

(b)

Figure 5.

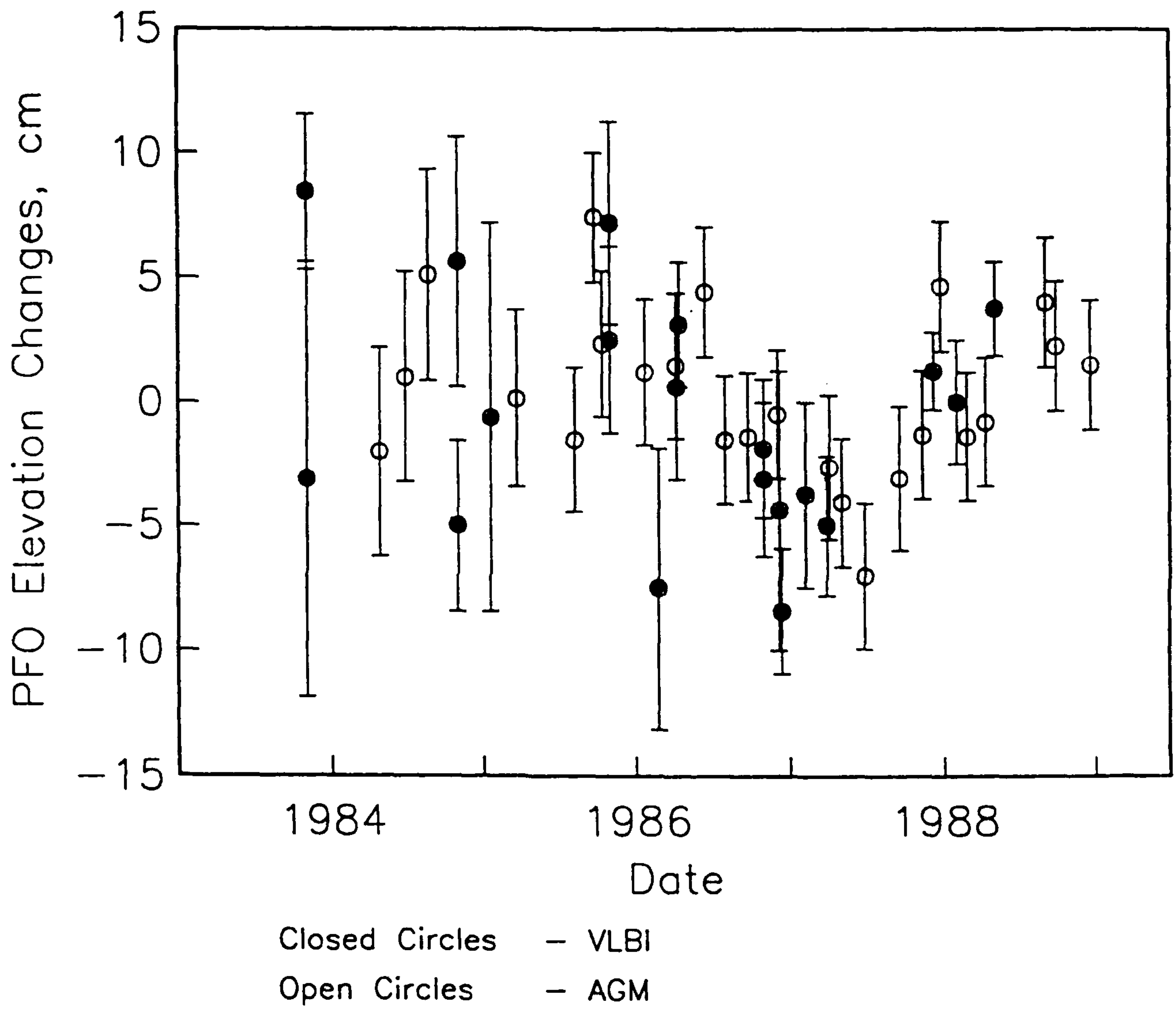

15
10
5
0
−5
−10
−15
PFO Elevation Changes, cm
1984
1986
1988
Date
Closed Circles — VLBI
Open Circles — AGM

Figure 6.

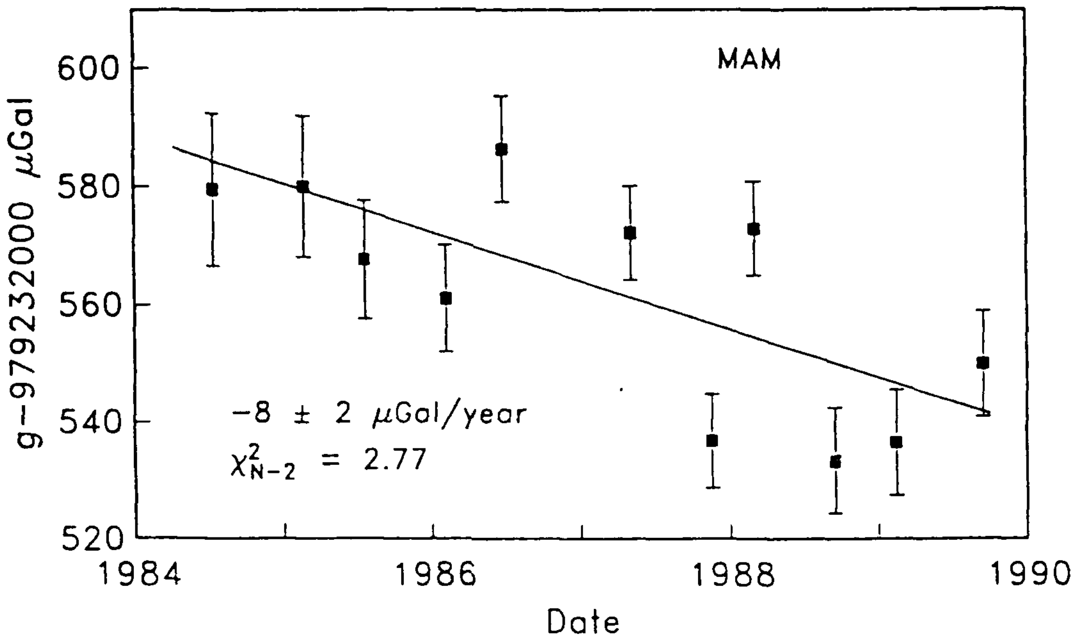


Figure 7.

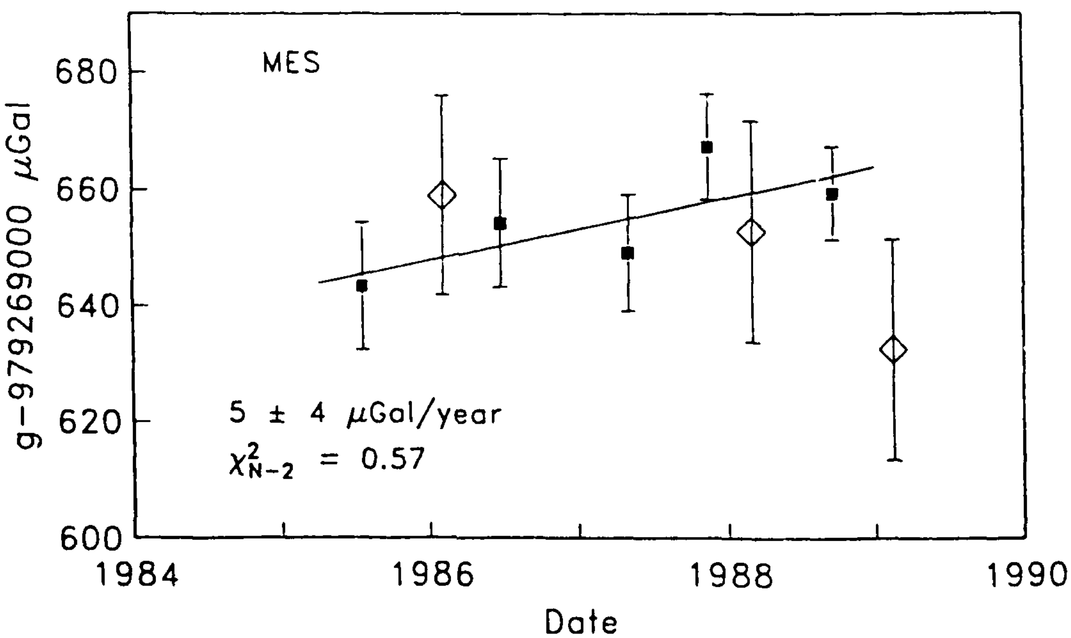


Figure 8.